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OVERVIEW OF AMORPHOUS SILICON (a-Si) PHOTOVOLTAIC INSTALLATIONS AT SMUD

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ABSTRACT

The Sacramento Municipal Utility District (SMUD) Solar Program has installed over 10 MW of photovoltaic (PV) systems including more than 2,000 kW of amorphous silicon (a-Si), thin film PV systems installed since 1994 in systems ranging from 1 kW to 700 kW. While lower in efficiency compared to the more traditional single-crystal silicon (c-Si) and polycrystalline silicon (pc-Si) PV modules, the significantly lower price per Watt of a-Si can often result in dramatic turnkey system savings despite increased area-related installation costs.

Thin film modules have shown good durability, long-term stability, and favorable long-term performance in the extensive field experience gained by SMUD. Results of independent, third party module testing is also presented along with an analysis of the key factors characterizing a-Si long-term performance. SMUD's experience with a-Si module durability and reliability is discussed along with the examination of various problems encountered, including a key area of concern, field cracking of unframed, glass-glass laminates. Based on SMUD's extensive experience with a-Si modules, specific background issues such as performance, durability and reliability, system design, supplier/process, and cost /pricing are discussed in this report.

1. INTRODUCTION

The Sacramento Municipal Utility District (SMUD) has the most extensive field experience with the widest variety of photovoltaic (PV) systems in the world today.[1, 2] Since 1984, SMUD has installed over 10,000 kW of PV in some 1,000 systems. These applications have ranges from small residential rooftop systems to the world's largest, single site, PV power station – the Rancho Seco PV system that is now at 3,500 kW. The SMUD Solar Program has installed over 2,000 kW of amorphous silicon (a-Si), thin film PV systems since 1994 in systems ranging from 1 kW to 700 kW. These have been installed on residential and commercial rooftops, as SolarPorts over parking lots, in building integrated PV (BIPV) applications in new commercial construction, and as large ground mounted arrays at PV power stations.

Thin film PV materials offer substantial advantages over longer-established crystalline PV materials. They typically use less than 1% of the semiconductor material that is consumed in crystalline products, are produced by techniques that are better suited to mass production, and require substantially less energy to manufacture. Each of these points help lead to substantially lower manufacturing costs compared to crystalline PV products. However, thin film PV modules in 2001 represented only about 14% of the global production of PV compared to the more traditional single-crystal silicon (c-Si) with about 35% market share, polycrystalline silicon (pc-Si) PV modules with around 47% market share, and the remainder being emerging thin films such as Cadmium Telluride (CdTe) and Copper Indium Diselenide (CIS).[3,4] Of the 14% represented by thin film modules, a-Si is by far the most advanced making up 8.6%, with a-Si deposited on c-Si accounting for another 4.6%.

While lower in sunlight-to-electricity conversion efficiency compared to the more traditional c-Si or pc-Si PV modules, the significantly lower price of a-Si can often result in dramatic turnkey system savings despite somewhat

Fig. 1: Hedge APS System

increased area-related installation costs. Where area constraints are not a significant factor, a-Si modules can provide cost-effective PV solutions in a wide variety of applications.

Amorphous silicon PV modules have shown good durability, long-term stability, and favorable long-term performance in the extensive field experience gained by SMUD. The primary areas where attention needs to be focused include proper packaging and handling to prevent damage during transportation, training installers to properly handle unframed glass laminates, and appropriate QA/QC at the factory to assure production of modules that consistently meet performance and reliability specifications. Each of these issues has been successfully addressed during the course of the SMUD Solar Program. Based on SMUD’s extensive experience with thin film modules, specific background issues such as performance, durability and reliability, design, supplier/process, and cost are discussed in the following sections.

2. THE SMUD THIN FILM PV EXPERIENCE

SMUD’s experience with thin film modules started with the Advanced Photovoltaic Systems (a predecessor to EPV) APS 50 modules starting in 1994 in a 100 kW substation system (Fig. 1). This was followed by the Solarex/BP Solar MST 43 and the Energy Photovoltaics Inc. EPV 40 modules. These systems that have ranged from 1 to 700 kW in applications including utility power station/substation ground mounted PV systems, SolarPorts, commercial and public building roof top PV systems, residential roof top PV systems, on top of barns, as a bleacher shade structure at a public pool, and for parking lot lighting. Thin film modules are also particularly well suited for building integrated projects due to their uniform visual appearance.

Since mid-1999 through mid-2002, about 170 kW of thin film (a-Si) modules have been installed in customer owned, residential systems under the PV Pioneer II Program. The systems are rated at the “stabilized” value, which determines the price of the system. Most customers are not aware of the fact that the initial output of the system will be substantially higher in the first couple of months of exposure while the modules degrade to their stabilized rated condition. Those who are aware of it are typically pleased with the “bonus” energy obtained during that period. Under the module supply contracts, SMUD only pays for modules based on the rating of a PV module after one year of degradation losses. The first year of degradation losses are absorbed by the manufacturer. This should be an industry standard for **ALL** PV module types from all suppliers.


Fig 2. Thin film PVPII System

3. PERFORMANCE ISSUES

The performance of thin film PV modules is one of the two key issues of concern generally voiced when evaluating the selection of PV module technology (the other key issue, durability, is discussed in the following section). Thin film modules, in particular a-Si modules, are considered to degrade in performance dramatically in comparison to c-Si and pc-Si. This perception of a “stability problem,” strengthened by early issues of thin film production quality control, have been major factors in reducing the level of acceptance of a-Si module technology to date. Since 1994 the extensive experience with a-Si modules under the SMUD PV Program demonstrates a level of performance quite comparable to that of c-Si and pc-Si products.

The a-Si module is subject to the Staebler-Wronski (SW) effect, where there is a pronounced decrease in performance upon exposure to light typically reducing the modules output by some 18% to 20% compared to its initial output. This effect is most pronounced in the first few months and gradually approaches a “stabilized” value after approximately 6 months. The real problem occurs when the initial output is taken as a “rated value” of output and performance over time is compared to that. The rated output value of an a-Si module should be set at the stabilized value after the SW effect has run its course. Independent testing of randomly selected modules for both rating purposes and determining longer term performance is conducted for SMUD by the Arizona State University Photovoltaic Test Laboratory (ASU-PTL). SMUD staff and contractors conduct additional field-testing.

For any particular module manufacturing process and production operation, the amount of degradation from initial conditions to stabilized condition can be determined quite closely, at least to a couple of percent for standard production runs. Sufficient QA/QC procedures should be put in place so that the average stabilized actual output value is the rated value or at least very close to it after a year of operation with a small distribution spread.

Extensive field experience at SMUD has shown that after 3 months a-Si modules operate at a point that is reasonably close to the stabilized value. After 6 months, the power is typically well within 10% of the stabilized value. A year provides more than ample time for a-Si modules to stabilize. Any differences after that point are due to either the long-term degradation of the module performance which is similar in magnitude to that of c-Si and pc-Si (typically less than 1% per year) or due to the seasonal annealing process that results in the sinusoidal season-to-season fluctuation of module performance for a-Si modules. The higher summertime ambient temperatures actually partially reverse the SW effect temporarily, but it returns with additional exposure to sunlight. This seasonal variation (which is clearly shown in the EPV 1,400 day test curves) can easily be 5% to 8% and tends to swamp out the ability to see the much smaller longer-term effect. The EPV 40 module is a typical dual-junction, a-Si, glass on glass module with a 40 watt STC rating. As can be seen in Fig. 3[5], with 4 EPV-40 modules (randomly selected) with over 1,000 days of exposure, the range of Pmax is from 36.5 to 41 watts for the 40-watt rated modules. Note that each module shows a seasonal variation of 3 to 4 watts and the average values for the 4 modules range only from 38 to 39.5 watts for the 40-watt rated modules, a degradation of 1% to 5% from the rated value.

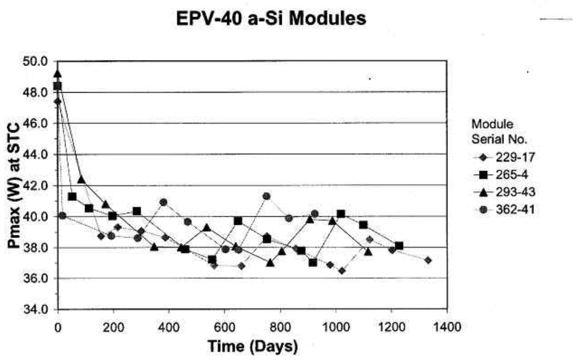
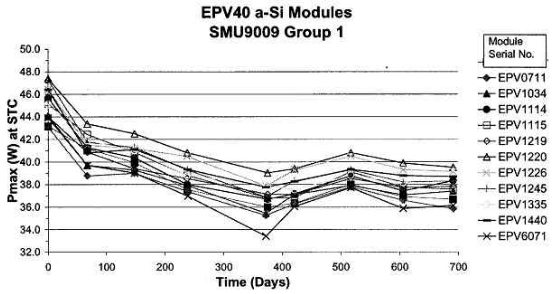


Fig. 3: EPV 40 modules Pmax Curves

Figure 4[5] shows a larger sample of EPV 40 modules with 600 to 700 days of exposure. These modules exhibited Pmax values of 36 to 41 watts for the 40-watt rated modules. When accounting for the seasonal variation, the average Pmax for the modules ranged from 38 to 44 watts and a group average Pmax of approximately 38 to 39 watts, about a 2.5% to 5% degradation of peak power from the rated value. From experience with longer cumulative exposure



Note different start dates for each module

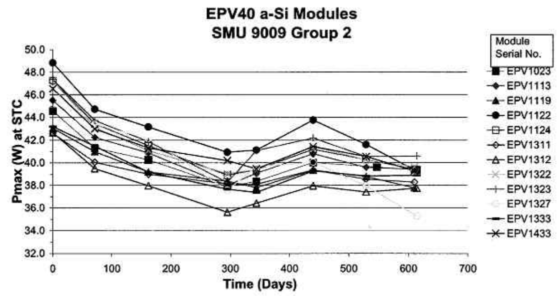


Fig. 4: EPV 40 modules test curves

times at SMUD, it is expected that this peak power value will hold fairly constant for a very long time (i.e. several decades) with a less than 1% per year average degradation superimposed on those values. This would be well within the typical 20-year/80% power or 25-year/75% power warranties.

Long-term peak power degradation is typically composed of three factors as shown in the idealized curve in Fig. 5 (after Delahoy[6]). The first is the degradation to the "stabilized" value (curve A). This is the initial degradation seen in the first year (Staebler-Wronski effect). Most of the decline is

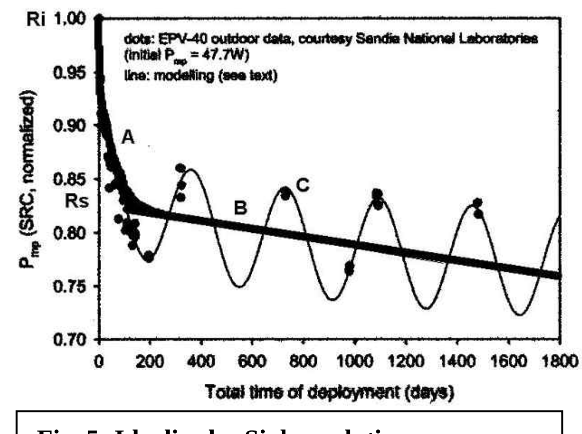


Fig. 5: Idealized a-Si degradation curve

actually seen in the first month or so and asymptotically approaches a "stabilized" Pmax value ideally equal to the module rated Pmax value. Then a seasonal variation of some 5% to 8% is seen with the Pmax cycling around the stabilized Pmax value (sine curve B). Superimposed upon this seasonal cycle is a gradual long-term degradation, typically of some 0.5% to 1% for the life span of the module (straight line C). Since the long-term degradation factor is much less than the cyclic seasonal variation, it is much harder to see and to accurately determine its value. Most studies that we have reviewed suggest that the long-term degradation of c-Si or pc-Si and that of a-Si are fairly comparable. Many of these studies quote a long-term degradation value of 1 to 2% annually with some as high as 1 to 5% annually. This is not an easy value to determine as it is often swamped out by other effects and differs radically with some materials that have been used in construction of modules. It is further compounded in the case of a-Si by the seasonal effects.

At SMUD, experience suggests much lower values of degradation, less than 0.5% per year, for modern modules in the Sacramento climate. With a-Si, depending on what times of year measurements are made, the seasonal effect may easily be mistaken for a value determining the long-term degradation of the module. This combination of three degradation mechanisms was investigated by the author (D.E. Osborn) at the University of Arizona Solar and Energy Research Facility[7] in the early-1980s and confirmed many times by others since then.

The a-Si PV systems have demonstrated very good system performance in the SMUD PV Program. For 36 residential PV Pioneer II systems with a-Si modules that had been fielded for at least 18 months and had at least 12 months of monthly production data beyond the initial 6 months, an average capacity factor (the ratio of actual output of a system over the year to the output at the system's rated value for 8760 hours [365 days X 24 hours per day]) of 18% was determined. This is somewhat higher than the design capacity factor and comparable with the capacity factors of similar crystalline systems. Another 12 a-Si residential PVPII systems were analyzed for their performance Index (PI -- ratio of actual energy output to the rated performance). As can be seen in Figure 6, these systems with the Solarex Millenia a-Si Modules and Omnion inverters demonstrated very good PIs with a high average PI of 104%, a low average PI of 55% and an average PI for the group of 12 systems of 80%. Service inspections of the lower performing systems found inverter, wiring and shade problems that resulted in the lower performances.

Since a new a-Si module has a higher output than a stabilized one, the inverter selected must be able to handle

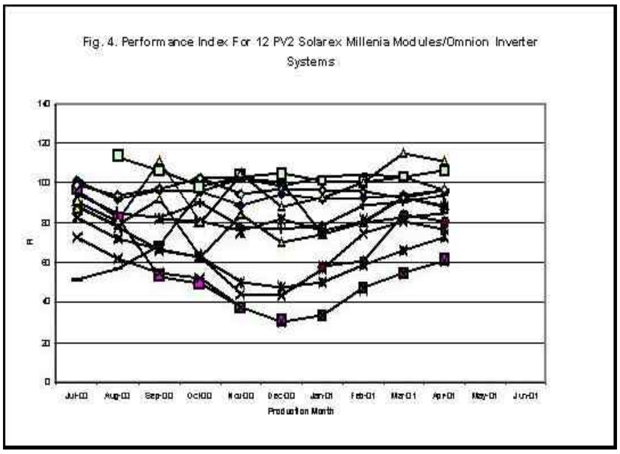


Fig. 6 PIs for 12 a-Si PV Pioneer II systems

this higher initial DC input. SMUD has found that there is typically not a need to oversize the inverter to account for this and thus incur additional cost for a larger inverter. Most of the initial degradation takes place early on so it is a fairly short-term problem. Additionally, the module is not producing peak output during most of the year nor over most of the day. When the short term module production does exceed inverter DC input limits, most inverters will handle it by simply cutting off at the limit, losing some of the excess energy produced or shut down until later in the day when DC power production is back to the design level.

4. DURABILITY/RELIABILITY ISSUES

PV modules need to operate reliability for 30 years or better, unattended, with minimal maintenance, and in the harsh outdoor environment. Fortunately, most major brands of modern PV modules seems quite up to this task whether thin film or crystalline.

To help assure the quality and performance of the PV systems under the SMUD PV Program, the PV manufacturers, suppliers and designers are contractually obligated to meet the key performance standards in place to assure quality PV equipment, system design, and installation procedures as well as an extensive quality assurance/quality control (QA/QC) program conducted by SMUD.

The SMUD PV installations using a-Si modules have performed well without any additional problems not experienced in c-Si or pc-Si module systems with one exception. When unframed glass-on-glass laminates are used, significant additional care must be taken to inspect for edge chips of the glass and to handle properly to avoid stress related cracks. These cracks can show up weeks after installation and are almost always due to edge cracks that propagate as a result of thermal or structural stress, mishandling in uncrating or installation (i.e. setting a module on its corner or knocking an edge), or by over-stressing the module during installation from excessive torque on the mounting bolts, lack of stress relief washers (rubber or nylon washers on mounting bolts), or unaligned mounting rails resulting in significant bending of modules. Through a modest amount of training for the handlers and installers, SMUD was able to quickly reduce a nearly 15% module failure/rejection rate down to about 1%. This special field training, while simple, is an absolute must when dealing with unframed, glass laminates.

Most of the a-Si modules that have been fielded by SMUD have been unframed laminates. Module framing does provide a module that is more resistant to damage in handling. Generally SMUD has found that module frames are mainly valuable until the PV system is installed. After that they add little value and actually enhance soiling. The major exception are framing systems that also provides simplified, lower cost installation on selected roof-types and can also provide a wiring chase. However, the benefit of the frame in lowering onsite installation costs must be greater that the cost of the frame to make this a worthwhile trade-off. The Solarex/BP Millennia Module Integra Frame is an example of this for use on composition shingle roofs.

While a serious problem with early thin film modules, SMUD has had no problems with edge sealing of a-Si modules. We have seen a few of the various “worms” and other blemishes that can develop or become more pronounced with age. Typically we have not seen any effect on performance due to these visible “defects.” Excessive “worming” can be a sign of delamination or other processes that may result in moisture intruding in to the silicon film layers and cause premature failure of the module and are a clear sign of poor QA/QC and should be addressed in that context.

The typical warranty on a-Si modules installed at SMUD is either 20 years at 80% of rated stabilized power or 25 years at 75% of rated stabilized power. These are power warranties that our end use customers seem to value. Because of SMUD’s own extensive field experience, long term module field testing at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL), accelerated aging tests done by various suppliers, and analysis of the failure modes of a-Si modules by SMUD engineers, SMUD fully expects well made a-Si modules to continue producing substantial electric power well beyond the warranty period. We treat them as a 30-year+ useful life expectancy. Experience at SMUD to date tends to confirm this assumption.

Other than the module cracking problem that is discussed above, there have not been any significant differences in module reliability between a-Si and c-Si/pc-Si PV modules deployed at SMUD. The differences in module reliability seem entirely due to the specific QA/QC procedures undertaken for a particular production run of modules rather than the module material. Where good manufacturing QA/QC procedures are followed, a-Si module reliability is very high, regardless of the module manufacturer or type. Where QA/QC slips, SMUD has observed a significant increase in problems.

5. NON-SMUD EXPERIENCES WITH A-SI PERFORMANCE, DURABILITY AND RELIABILITY

The favorable experience that SMUD has had with a-Si, while more extensive than most, is quite similar to that of other documented experiences in various parts of the world. As with SMUD’s findings, the experience with a-Si is very dependent on the quality of the manufacturer’s QA/QC efforts and their commitment to quality production.

Gottschalg, et al.[8], examined the performance of dual junction a-Si systems that had been operating for several years in a wide variety of climate zones. The systems were located in Brazil, China, Spain, Switzerland, and the UK. They found the initial degradation to be about 20% typically stabilizing to a value corresponding to the system design value. For well designed and properly installed systems they found that “amorphous silicon systems operating in different climatic conditions can exhibit very high performance ratios,” finding performance ratios of 86% to near 100% for these systems. They also found that “all systems exhibit a relatively stable operation after the initial degradation.”

Ruther, et al.[9], examined a carefully monitored a-Si system in Brazil over a four year operating period. They found a high performance ratio of 83% AC and 91% DC. They also noted that a-Si are particularly well suited to warmer climates compared to crystalline modules due to the smaller negative temperature coefficient of a-Si compared to c-Si and pc-Si and due to the noticeable increase of thermal annealing caused by higher operating temperatures reducing the degree of initial degradation. They report “a-Si PV systems operating well and at stabilized output levels after an initial light-induced degradation, with performance ratios comparable with those of traditional crystalline silicon (c-Si).”

Duke, et al.[10], in their paper on the Kenyan Solar Home Market, found very large differences in the quality, and thus performance, of a-Si modules in the field depending on the manufacturer. They point out that the a-Si modules had stabilized output values less than the rated value of the modules with even the high quality manufacturers’ modules showing a stabilized performance of only 90% of the rated value. They then point out that “average performance levels for crystalline modules are also often just above the warranty level, which is typically about 90% of rated power.” This is very similar to the SMUD experience for all types of module technology and underscores the need for manufacturers to do a better job in accurately rating modules and in their QA/QC programs. It is also a major reason that SMUD pays for modules on a “per stabilized watt basis” and conducts independent testing. Duke, et al. also point out that “well-made a-Si modules appear to exhibit modest long-term degradation that is roughly comparable to that of crystalline modules.” While they make a major point of the difficulty of predicting the performance of a-Si due to the complexity of the degradation mechanisms, it appears that these matters are understood well enough to permit careful and high-quality manufacturers to determine the proper and accurate (to a couple of percent) stabilized rating for modules with the main outstanding issue of where in relation to the seasonal variation is the “stabilized” point positioned.

Sandia National Laboratories has carefully performed an extensive monitoring and module analysis to characterize the stabilization and performance of a-Si modules[11]. After performing detailed performance evaluation of multiple modules from four different manufacturers over several years of continuous outdoor exposure in New Mexico (including modules from EPV and BP of the types widely used in the SMUD program). King, et al. found that The majority of the modules tested reached a “stabilized” power level about 20% below the initial (1st day) power after about 1 year and the effect of seasonal oscillation (thermal annealing) accounted for about ±4% variation from the “stabilized” level.

King also noted that due to the combination of seasonal thermal annealing and seasonal solar spectrum distribution influences on a-Si module efficiency is “about 13% higher in the summer than winter, consistent with field experience for a-Si systems.” Crystalline systems exhibit just the opposite behavior with significantly degraded performance under high summer temperatures. This is a significant advantage to a-Si modules in areas with summer utility peak loads.

6. DESIGN, SUPPLIER/PROCESS AND COST ISSUES

Handling and packaging issues are key issues for any glass based PV module. PV modules should be packaged in a good quality, slot-cut, closed-cell foam in a sturdy wooden crate or water-resistant shipping cardboard with sufficient compressive strength. For unframed laminates, the packing is all-important and must be very well thought out and tested. Training for handlers and installers, as discussed above, is also essential.

Since a-Si modules have a lower conversion efficiency than crystalline products, based on current relative efficiencies, an a-Si system will require approximately double the space of c-Si or pc-Si to obtain the same power output. This of course increases the area related portions of the installation cost. In evaluating bids for module supply, SMUD adjusts the bid price by a factor to account for the area related installation and balance of systems (BOS) costs. SMUD is able to use lower efficiency modules when the relative price of those modules is lower after taking into account the increased area related costs that are incurred due to the lower efficiency. Based on extensive experience and installation contracts SMUD has found that typical a-Si systems, compared to typical c-Si module systems, add about \$0.50/W to \$0.80/W in increased area related installation costs for the 5% to 6% efficient a-Si modules that SMUD has typically fielded in simple Unistrut-type roof systems and in non-tracking, ground mounted systems. The lower end of this range is for an experienced installation crew, well up on the learning curve and using pre-panelized sub-arrays and well established procedures and designs on clean, uncluttered roofs under long-term installation contract with SMUD – all of which help to reduce the area dependent costs. So a-Si module prices must be at least this amount lower than c-Si or pc-Si to be cost competitive.

Fig. 7: East End a-Si BIPV Curtain Wall

SMUD’s contract price for a-Si modules with EPV started at $2.50/W in 1998, with annual scheduled price reductions to $1.50/W for 2002. However, SMUD never received any a-Si PV modules priced lower than $1.75/W. Due to various problems experienced by SMUD’s main a-Si supplier –

primarily delays in getting the new CalSolar a-Si PV factory to normal production levels and an on-going under-capitalization affecting the supplier's ability to properly resolve production problems as they arose -- a-Si module prices stalled out at about $2.20/W to $2.25/W. For a-Si to effectively compete against c-Si and pc-Si modules today, utilities and other large volume purchasers need to see closer to $2.00/W.

Fig. 8: 500 kW Solarport (250 kW a-Si)

Post subsidy PV systems will require module prices of about $1.50/W (in large quantities) and with efficiencies of at least 7% to 10%. These factors can be considered as necessary targets for thin film modules and are ones that the industry seems capable of meeting in the necessary time frame. They are targets compatible with the USDOE/US PV Industry Roadmap[12] and ones that will continue the strong and expansive PV industry as US incentive programs, like the California Buydown Program, fade towards the end of this decade. Thin film PV module technologies, including a-Si, are a key path for the long-term goal of making PV a mainstream supplier of electric services.

7. CONCLUSIONS

Based on the extensive experience in the SMUD Solar Program -- having installed over 2,000 kW of amorphous silicon (a-Si), thin film PV systems since 1994 in systems ranging from 1 kW to 700 kW -- and on other reported experience worldwide, it is clear that thin film PV materials such as a-Si offer substantial potential advantages over the better-established crystalline PV materials. While lower in conversion efficiency compared to the more traditional single-crystal silicon (c-Si) and polycrystalline silicon (pc-Si) PV modules, the lower price of a-Si can often result in dramatic turnkey system savings despite increased area-related installation costs.

Amorphous silicon PV modules have demonstrated good durability, long-term stability, and favorable long-term performance in the extensive field experience gained by SMUD that has been confirmed by independent, third party module testing. Under its module supply contracts and warranties, SMUD pays for modules on a $/delivered watt based on the rating of a PV module after one year of degradation losses. The first year of degradation losses are absorbed by the manufacturer. This should be an industry standard for all PV module types from all suppliers.

When special handling care and training is taken, unframed glass-glass laminate thin film modules can be fielded very successfully. Other differences in module reliability compared to c-Si and pc-Si were shown to be due to the specific QA/QC procedures undertaken for a particular production run of modules rather than he module materials. Where good manufacturing QA/QC procedures are followed, a-Si module reliability can be very high, regardless of the module manufacturer or type. Where QA/QC slips, SMUD experienced a significant increase in module related problems. The success in application of a-Si modules is very dependent on the quality of the manufacturer's QA/QC efforts and their commitment to consistent quality production.

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